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An Empirical Approach for Detecting Crop Water Stress Using Multispectral Airborne Sensors

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Summary. Irrigation scheduling can be improved by directly monitoring plant water status rather than depending solely on soil water content measurements or modeled evapotranspiration estimates. Plants receiving sufficient water through their roots have cooler leaves than those that are water stressed, leading to the development of the crop water stress index, which uses hand-held infrared thermometers as tools for scheduling irrigations. However, substantial error can occur in partial canopies when a downward-pointing infrared thermometer measures leaf temperature and the temperature of exposed, hot soil. To overcome this weakness, red and near-infrared images were combined mathematically as a vegetation index, which was used to provide a crop-specific measure of vegetative cover. Coupling the vegetation index with the paired radiant surface temperature from a thermal image, a trapezoidal two-dimensional index was empirically derived capable of detecting water stress even with a low percentage of canopy cover. Images acquired with airborne sensors over subsurface drip-irrigated muskmelon (*Cucumis melo* L.) fields demonstrated the method's ability to detect areas with clogged emitters, insufficient irrigation rate, and system water leaks. Although the procedure needs to be automated for faster image processing, the approach is an advance in irrigation scheduling and water stress detection technology.

In arid environments, high daytime temperatures coupled with low humidity cause a large amount of water to evaporate from the soil surface and transpire through the leaves of crops (and weeds). The transition from no stress to an economically harmful level of water stress can occur quite rapidly, making irrigation timing a major concern of growers.

Four methods are used by growers to schedule irrigation: fixed irrigation intervals, judging plant condition by eye, determining soil water content, and estimating crop water use from meteorological data.

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Visual assessment of plant water status, while time consuming, can be remarkably effective on some crops when performed by an experienced grower. However, crops and profit margins are likely to suffer during the years necessary to learn this art. Regular soil sampling to assess water depletion is a good method, but it must assume uniformity in soil water-holding capacity for large areas so that a few point measurements suffice to characterize water retention properties. The method also assumes a uniform plant density and, hence, the same transpiration per unit area over an entire field, which is often not the case. Similarly, evapotranspiration (ET) models assume a freely transpiring reference crop with uniform canopy cover and soil type within a field.

Hand-held infrared thermometers (IRTs) are effective tools for detecting water stress in crops. These devices are radiometers sensitive to thermal electromagnetic radiation in the 8- to 12-μm band, which can be converted to surface temperature for targets (such as vegetation) having a high emissivity. As the water supply in the root zone becomes depleted, transpiration is reduced, solar energy normally absorbed through evaporation within the leaves is converted to heat, and the leaf temperature increases relative to air temperature. The method is particularly effective in hot, arid environments where the leaf temperature of a well-watered plant can be >10 °C cooler than the air when the relative humidity is very low.

A major difficulty in applying infrared thermometry to irrigation management is that nadir-looking instruments cannot be used if exposed soil is within the sensor's field of view. A dry bare soil can have a midday temperature that is >20 °C above air temperature and 30 °C higher than a nonstressed canopy temperature (Jackson, 1985). One can easily see how even a small percentage of exposed soil in the field of view of an infrared thermometer can produce an erroneously high composite temperature, leading to premature irrigation. The problem has been circumvented by carefully angling hand-held IRTs to exclude bare soils (Jackson et al., 1981), but airborne or satellite-based monitoring was only feasible under near full canopy cover conditions (Millard et al., 1978). A means of compensating for various amounts of exposed bare soil was necessary to allow the method to be used throughout the growing season.

The crop water stress index

Idso et al., (1981) developed an empirical crop water stress index (CWSI) for several crops, which used measured radiant plant canopy temperature in conjunction with the air temperature and vapor-pressure deficit at 1.5 m above the plant canopy. For a particular vapor-pressure deficit and air temperature (T_a), minimum (nonstressed) canopy temperature (T_{cm}) and maximum (fully stressed) canopy temperature (T_{cx}) were calculated. The measured canopy temperature (T_{cr}) was then used to calculate the empirical index–Eq. [1]:

$$CWSI = (T_{cr} - T_a) - (T_{cm} - T_a)/(T_{cx} - T_a) - (T_{cm} - T_a)$$

such that a CWSI of 0 would indicate no water stress and 1 would be maximum stress.

Jackson et al. (1981) analyzed the phenomenon in terms of energy dynamics. While the inputs necessary for this calculation are more complex, the resulting theoretical index can be used in any environment. Monteith (1973) described the energy balance for a crop as Eq. [2]:

$$Rn = G + H + \lambda E\tau$$

where R_n = the net radiant heat flux density, G = the soil heat flux density, H = the sensible heatflux density, and $\lambda E\tau$ (the product of the evapotranspiration rate $E\tau$ and the heat of vaporization λ) = the latent heat flux density to the air; all units being in watts per square meter. In short, the radiant energy reaching Earth's surface that does not leave Earth's surface as radiant energy is used to warm the soil, warm the air above the surface, or evaporate water. The soil heat flux term (G) can be estimated as ≈35% of R_n for bare soils and 10% of R_n for full cover canopies (Clothier et al, 1986). For dense crops (Allen, 1986; Penman, 1948), H and λE_t can be expressed as Eq. [3]:

$$H = C_v(T_c - T_a)/r_a$$

and Eq. [4]:

$$\lambda E\tau = C_v(VPD)/\gamma(r_a + r_c)$$

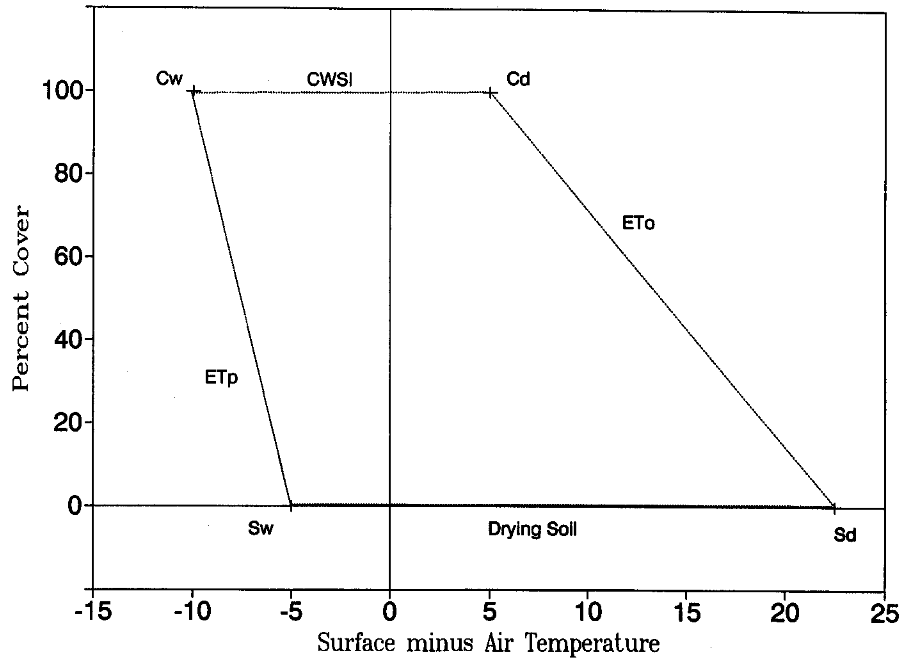
where C_v = the volumetric heat capacity of air (J °C^{-1}·m^{-3}), T_c = the crop foliage temperature (°C), T_a = the air temperature (°C), VPD = the water vapor-pressure deficit of the air (kPa), γ = the psychrometric constant (kPa °C^{-1}), r_a = the aerodynamic resistance (s·m^{-1}), and r_c = the canopy resistance (s·m^{-1}) to vapor transport. Combining Eqs. [2], [3], and [4] and solving for temperature we have Eq. [5a]:

$$(T_c - T_a) = r_a(R_n - G)/(C_v)\gamma(1 + r_c/r_a)/\Delta + \gamma(1 + r_c/r_a) - VPD/(\Delta + \gamma(1 + r_c/r_a)$$

where Δ = the slope of the saturated vapor pressure–temperature relation (kPa °C^{-1}) (Monteith and Seicz, 1962).

When the crop is not experiencing water stress, the canopy resistance is at a minimum and the expected minimum canopy temperature minus air temperature would be Eq. [5b]:

Fig. 1. A percent cover – temperature trapezoid as defined by the four vertices. Cw = the minimum temperature expected of a well-watered crop canopy, Sw = minimum (wet) soil temperature, Cd = maximum, nontranspiring canopy temperature, and Sd = maximum (dry) soil temperature. The expected temperatures at potential evapotranspiration (ET_p) for various percentages of canopy cover constitute the left edge of the trapezoid, while surface temperatures expected under conditions of no evapotranspiration (ET_0) constitute the right edge.



$$(T_c - T_a)_m = r_a(R_n - G)/(C_v)\gamma(1 + r_{cm}/r_a)/\Delta + \gamma(1 + r_{cm}/r_a) - VPD/\Delta + \gamma(1 + r_{cm}/r_a)$$

where r_{cm} = the minimum canopy resistance of the crop under study.

A fully stressed crop would experience nearly complete stomatal closure, and, since canopy resistance is directly proportional to stomatal resistance, a maximum r_c value (r_{cx}) would produce a more positive leaf minus air temperature as in Eq. [5c]:

$$(T_c - T_a)_x = r_a(R_n - G)/(C_v)\gamma(1 + r_{cx}/r_a)/\Delta + \gamma(1 + r_{cx}/r_a) - VPD/\Delta + \gamma(1 + r_{cx}/r_a)$$

Equation [5b] defines the nonstressed endpoint of the theoretical CWSI, which, in practice, is the difference between the temperature of a full-cover canopy transpiring at potential ET and the air temperature. Likewise, Eq. [5c] describes the canopy minus air temperature when plants are fully stressed and ET is essentially zero.

The vegetation index–temperature (VIT) trapezoid

Moran et al. (1994) expanded on the CWSI concept by predicting the temperature extremes of dry and wet bare soils and then using a remote measurement of the amount of vegetation present to determine the relative influence of each (canopy and soil) component. Bare soil analogues of Eqs. [5b] and [5c] were developed, the main difference being in the treatment of canopy resistance and soil heat flux. A very wet soil surface evaporating at the potential rate would essentially have no barriers to vapor transport, and the r_c analogue would be zero. Under such conditions Eq. [5b] simplifies to Eq. [6]:

$$(T_o - T_a)_m = (r_a(R_n - G)/C_v) \times \gamma/(\Delta + \gamma) - VPD/(\Delta + \gamma)$$

where T_o = the soil temperature and $(T_o - T_a)_m$ = the minimum soil minus air temperature. A completely dry bare soil, on the other hand, would have an r_c analogue approaching infinity, so that in Eq. [7]:

$$(T_o - T_a)_x = r_a(R_n - G)/C_v$$

where $(T_o - T_a)_x$ = the maximum soil temperature minus air temperature.

If one were to create a two-dimensional space with percent canopy cover as the vertical coordinate and surface temperature minus air temperature as the horizontal coordinate, the four points described by Eqs. [5a], [5b], [6], and [7] form the vertices of a trapezoid as shown in Fig. 1. A measurement of percent cover and surface minus air temperature for any discreet area of ground would result in a pair of coordinates that fall somewhere within this polygon. The lines connecting adjacent vertices have particular meaning. The line from the upper left to upper right vertex is the range of possible canopy temperatures from a freely transpiring, well-watered full canopy (vertex C_w) to that of a highly stressed, nontranspiring canopy (C_d) and is the original CWSI. Coordinate pairs falling on the line connecting the upper left (C_w) vertex to the lower left (S_w) vertex describe potential evapotranspiration (ET_p); that is, no plants are experiencing water stress, and whatever soil is visible has a very wet surface. A line connecting the upper right (C_d) and lower right (S_d) vertices defines the zero ET (ET_0) condition. The bottom line, connecting the lower left (S_w) and lower right (S_d) vertices, describes soil surface moisture, with unrestricted evaporation at the extreme left, a patchy, drying surface at $T_o - T_a \approx 0$, and a completely dry soil with no evaporative cooling to the extreme right. A trapezoid's thermal dimensions are specific for crop type and meteorological conditions.

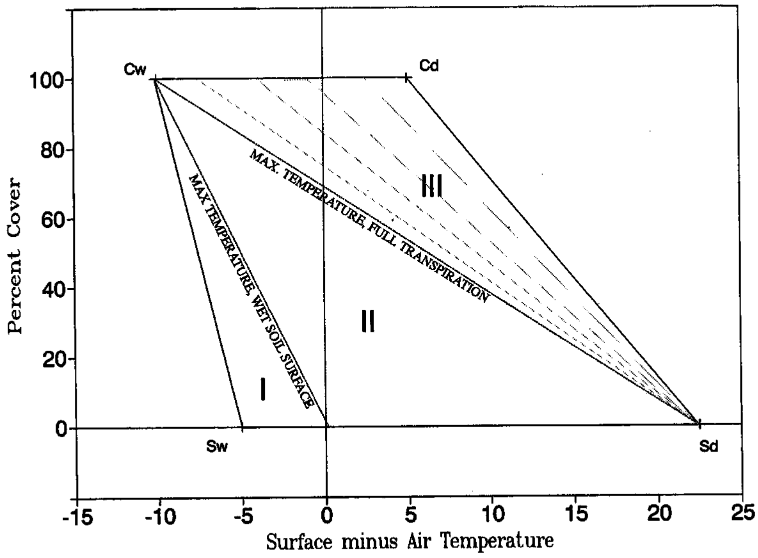


Fig. 2. The percent cover – temperature trapezoid divided into three descriptive zones: Zone I = nonstressed plants with a wet soil background, Zone II = nonstressed plants with a drying soil background, and Zone III = some degree of water stress and a completely dry soil background.

Two other lines (Fig. 2) can be drawn in the trapezoid that have particular significance to farm management. One is a diagonal from the upper left (C_w) vertex to the lower right (S_d) vertex. VIT pairs falling on this line define the condition where plants are transpiring freely but no evaporation is occurring from the soil surface; the canopy component is at minimum temperature and the soil component is at maximum temperature. Any coordinate pair falling to the right of this diagonal indicates that the canopy temperature must be greater than the minimum and the crop must therefore be experiencing some degree of water deficiency. The other diagonal of interest runs from the upper left vertex to the bottom line at $T_o - T_a = 0$. As a soil evaporating at less than potential will have a surface temperature greater than air temperature (Idso et al., 1975) any coordinate pair falling to the left of this line must have a wet soil surface.

If one assumes that the exposed soil portion of a mixed surface will dry before the root zone, the trapezoid can be divided into three zones as seen in Fig. 2: Zone I with a wet soil surface and maximum transpiration, Zone II with a dry soil surface but still no reduction in transpiration, and Zone III with a dry soil surface and some degree of plant water deficiency. While the soil surface beneath a dense canopy can remain damp for several days after irrigation, this surface is not visible to an overhead radiometer and need not be considered. Zone III can be further divided vertically into a fan-like pattern, with each subdivision from left to right representing an increasing level of water deficiency. For sparse cover (<15%) the temperature spread between nonstressed and completely stressed conditions is too small to be useful, but otherwise Zone III is a crop water stress index that operates with partial canopy cover.

While there is no precise remotely-sensed equivalent to percent canopy cover, there is often a characteristic relationship between reflectances in the red and near-infrared wavelengths and the amount of vegetation present for any particular crop and, in turn, a relationship between the amount of vegetation present and percent cover for that crop. The red/near-infrared relationships are called vegetation indices (VIs), and one that eliminates some of the undesirable soil background effect is the soil adjusted vegetation index or SAVI (Huete, 1988), as shown by Eq. [8]:

$$SAVI = (\rho_{nir} - \rho_{red})/\rho_{nir} + \rho_{red} + L) \times (1 + L)$$

where ρ_{nir} and ρ_{red} are near-infrared and red reflectances, respectively, and L is assumed to be 0.5 for most conditions. A bare soil has a SAVI of ≈0.07 in the

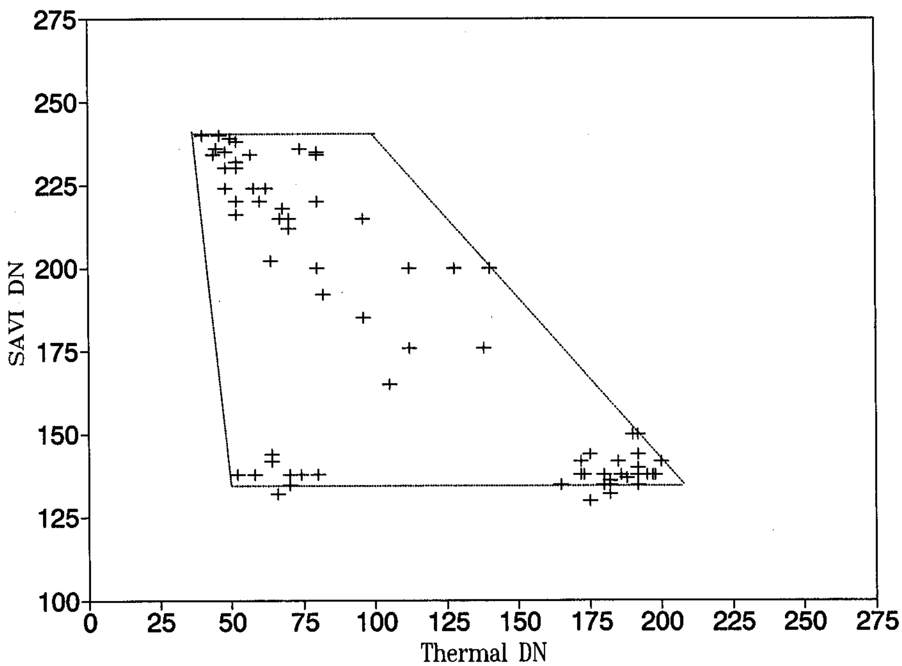


Fig. 3. Vegetation index – temperature (VIT) pairs used to delimit the VIT trapezoid. The pairs represent the extreme values extracted from several images of melon fields acquired within 20 min. Abnormally low vegetation indices from deep water and man-made surfaces were not included in the trapezoid.

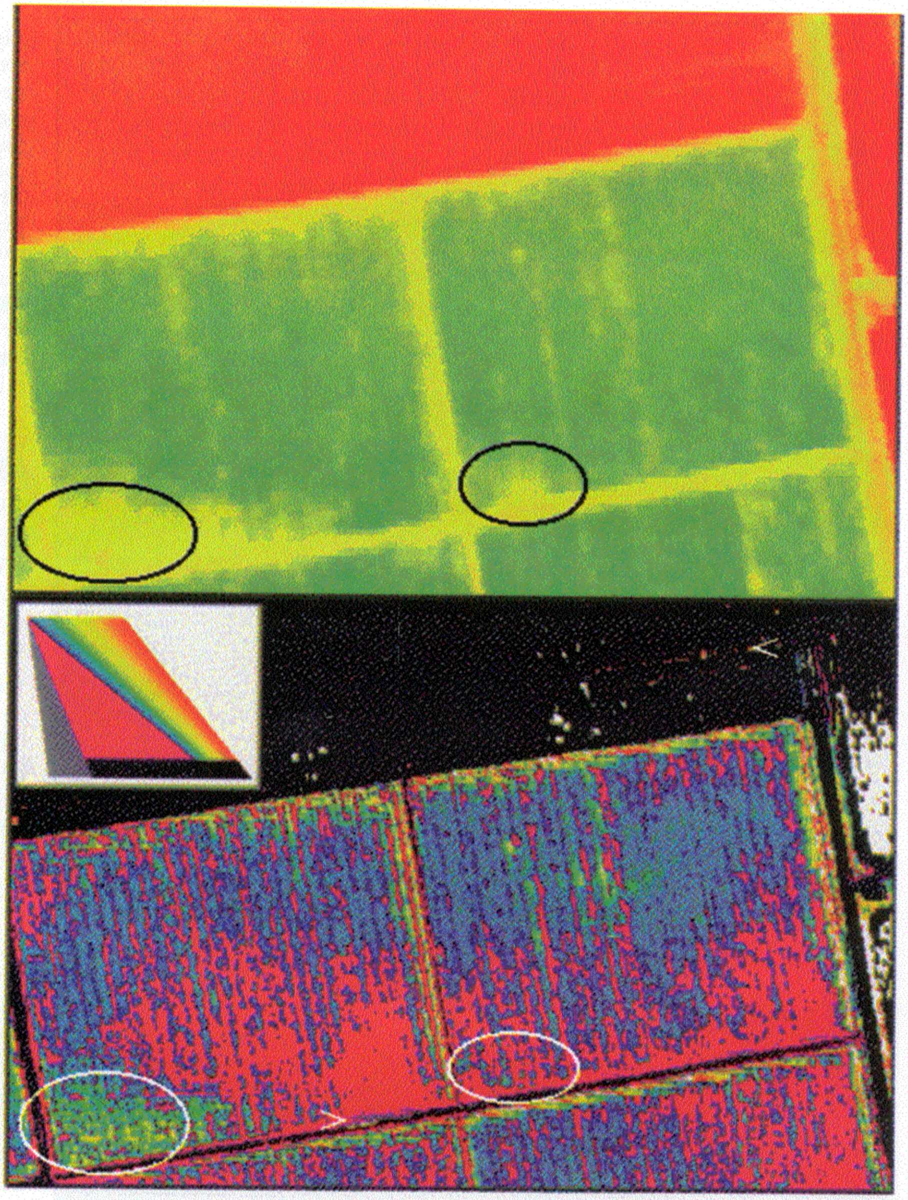


Fig. 4. (top) **Thermal image of two adjacent melon fields: red = relatively high temperatures, yellow = moderately high, green = moderate, and blue = low temperatures. The two warm areas at the bottom left corner of each field (circled) have thin vegetation caused by previously clogged emitters in the subsurface drip irrigation system.** (bottom) **CWSI image of the same fields derived from the VIT trapezoid. The zone color scheme (insert) shows nonstressed plants as magenta, plants with mildly reduced transpiration rates as blue and green, and stressed plants in yellow and orange. Areas with little or no vegetation over dry soil are black, while areas with a wet soil surface are colored gray. Highly stressed postharvest plants can be seen in the upper right (<), and a small leak in the drip system can be seen at the bottom of the left hand field (>).**

area of study, and the maximum detectable amount of vegetation has a SAVI of ≈0.84. The relation between a normalized difference vegetation index and percent cover is linear or nearly so (Jackson et al., 1980) and the SAVI's extreme values can, with caution, be substituted for 0% and 100% cover on the vertical axis of the trapezoid for crops with high leaf area to percent cover ratios such as cotton. Rapidly spreading plants such as melons approach full cover before the VI signal becomes saturated, and a lower SAVI should be used for 100% cover.

Empirical approach

A disadvantage of the theoretical CWSI model is its dependence on several inputs that may be difficult to assess. For example, aerodynamic resistance is affected by wind speed and, to a lesser degree, canopy architecture. Minimum canopy resistance may change with leaf age, and soil heat flux is estimated from net radiation, which is in turn an approximation derived from solar radiation, which must be measured. Also, soil temperatures can be affected by slope and aspect of the surface and by previous meteorological conditions, such as cloud shadows several minutes before image acquisition.

On farms in the southwestern United States, where evaporative demand is high, there is commonly sufficient variety in surface conditions to construct a trapezoid empirically with only a few easily obtainable inputs. For example, imagery of a large farm or several adjacent farms often include fields with soil surfaces still wet from recent irrigation and fallow fields with completely dry, bare soil surfaces that define the limits of the bottom (bare soil) edge of the trapezoid. If sufficient vegetation is present in the recently irrigated fields, the slope of the left (ET_p) edge can be determined. This leaves only three inputs necessary to delineate the trapezoid: 1) the canopy temperature of that crop (relative to air temperature) when completely stressed, 2) the VI at which the crop in question normally reaches 100% ground cover, and 3) the air temperature at the time of image acquisition. Inputs 1 and 2 are characteristic of the particular crop and do not depend on meteorological conditions. They can be determined beforehand in separate experiments. The completely stressed canopy temperature can be determined by cutting the stems of adjacent representative plants and monitoring the temperature of the cut-stem canopy in place with an infrared thermometer until the difference between leaf and air temperatures become asymptotic, be-

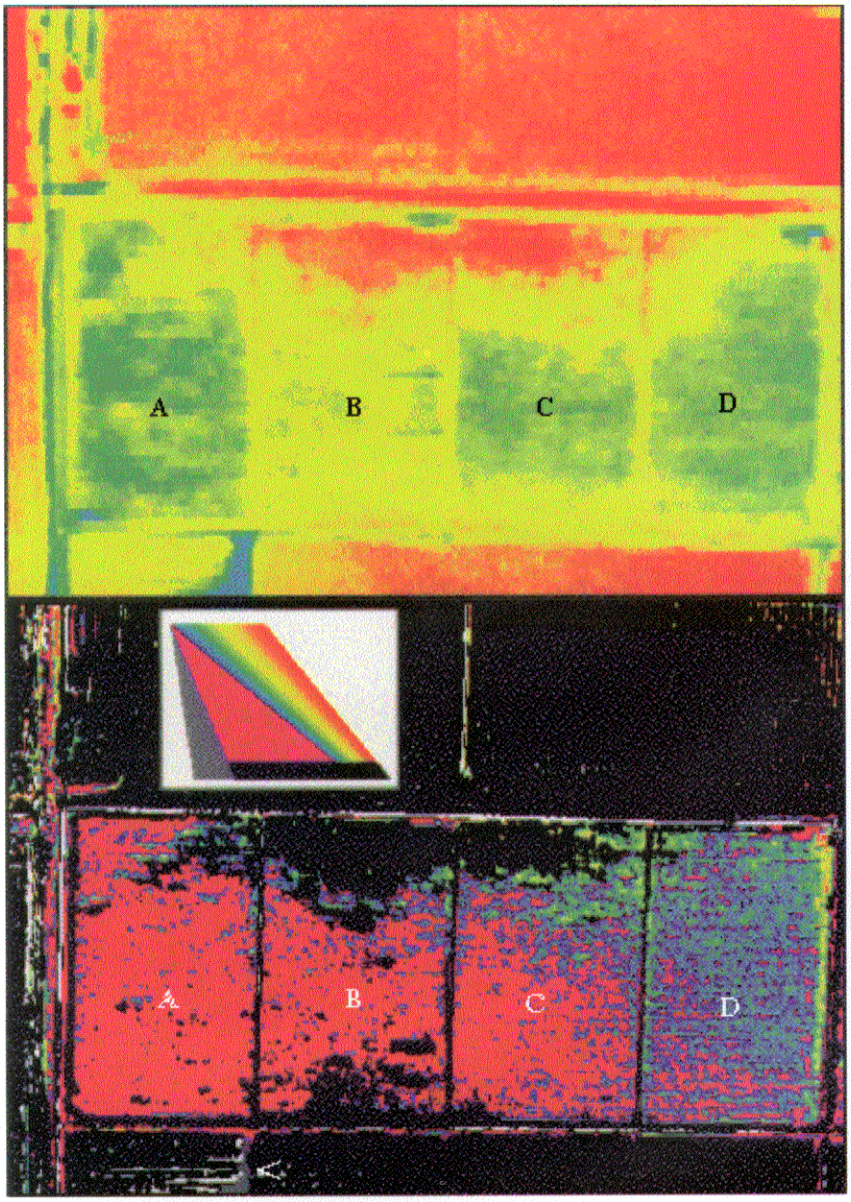


Fig. 5. (top) **Thermal image of four sections of a melon field that had suffered nematode damage. The color scheme is similar to that in Fig. 4. Section B of the field is warm because of low canopy cover.** (bottom) **CWSI image of the same field. The color scheme (insert) is the same as in Fig. 4. Note that section B, which appeared the warmest in the thermal image, was not water stressed, while section D displayed a slight deficit. A canal overflow can be seen as a gray area (<) at the bottom of the image.**

ing careful that wilting leaves do not allow the soil background to come into the view of the instrument. Alternatively, if some maximally stressed plants are known to exist in the images, the slope of the ET_0 edge can be inferred directly. Determining the VI at which 100% canopy cover can be expected need only be determined once for a particular variety and row spacing. Air temperature, normally measured 1 to 1.5 m above the canopy (screen height), can be recorded by a weather station or simply obtained by a ground observer during the overflight. The VIT trapezoid can then be created with no further inputs.

The VIT pairs of all surfaces in the images should fall within the bounds of the trapezoid. Exceptions include deep open water, desert vegetation, and artificial structures, any of which may exhibit temperatures and VIs outside the range of those for the crop/soil composite being monitored.

Materials and methods

A melon farm located ≈100 km west of Phoenix, Ariz., was overflown at 1400 HR on 15 Sept. 1994 with a light aircraft carrying an Inframetrics model 760 thermal scanner. The scanner's detector was kept chilled to 40 °C below ambient temperature by a sterling motor and contained an internal temperature reference, which was sampled at 60 Hz. The scanner was equipped with a lens having a 20° horizontal field of view (fov) and filtered to a bandwidth of 8.0 to 12.0 µm. The dynamic range was manually set from 20° below to 30° above the 34 °C screen height air temperature. Two Dycam model 3 digital cameras having a 24° fov were specially manufactured without infrared blocking filters and fitted with Omega Optical red (0.600 to 0.670 µm) and near-infrared (0.780 to 0.880 µm) interference filters. Each of these cameras was capable of storing 32 eight-bit digital images internally. The two digital cameras and thermal scanner were rigidly attached to each other and extended out the doorway of the airplane during image acquisition. An Omnidata model 706 polycorder was used to trigger the digital cameras and simultaneously save a digitized thermal image to a floppy disk. The aircraft was flown at an altitude of 2300 m above the ground, providing a spatial resolution of ≈4 m in the thermal band and 2 m in the optical bands. The sky was cloud free at the time of overflight. Ten images were acquired of areas containing fallow fields that had not been irrigated for several months, saturated bare soil surfaces on the edges of fields currently being irrigated, nonstressed melon canopies with 100% cover, and highly stressed postharvest partial canopies that had not been irrigated for 2 weeks. Using Terra-Mar MicroImage image processing software, the thermal and near-infrared band images were registered (spatially matched) to the red band image and a SAVI was calculated for each of the images based on digital number (DN), as no surface reflectance standard was deployed and the cameras had not been radiometrically calibrated. Scatter plots were prepared using the thermal DN as the abscissa and the corresponding VI pixel DN for the ordinate.

The VI DN corresponding to 100% plant cover was determined using images of fields that had a full range of cover and a wet soil surface from recent surface irrigation. VIT scatter plots of these images provided a clearly delineated ET_p (left) trapezoid edge. Temperatures decreased linearly with increasing VI along the ET_p edge up to a VI DN of ≈240, above which the ET_p edge became vertical. The VI DN of 240 was therefore used as effective 100% green leaf cover.

Using the extreme VI–temperature pairs of all images, a VIT trapezoid was constructed. Vertices for dry bare soil, wet bare soil, and well-watered full canopy were determined directly from the scatter plot, while the highly stressed 100% cover canopy temperature was inferred from an extrapolation of the ET_0 (right) edge formed by the postharvest partial canopies (Fig. 3) to the VI DN corresponding to full cover.

A color code was assigned to the empirically derived trapezoid, with Zone I assigned gray (wet soil surface) and Zone II assigned magenta (no stress). A fan-shaped color code for Zone III was assigned with a progression of blue, green, yellow, orange, and red, indicating increasing levels of water stress (Fig. 4, insert). Areas with very little or no vegetation over dry soil were made black, and areas whose VIT pairs fell outside the trapezoid limits were coded white. Since most of the muskmelon fields imaged had subsurface drip irrigation, a wet surface (Zone I) would indicate either a leak in the system or excessive irrigation and would be of interest to the grower.

Results and discussion

The CWSI image derived from the VIT trapezoid provided a more accurate understanding of the fields' water status than thermal images alone. Two 32-ha melon fields shown in Fig. 4 suffered from clogged emitters. The upper half of the figure is a thermal image of the fields showing areas of clogged emitters as two distinct warm areas coded in yellow near their lower (southern) edge. Ground observation showed that these areas had more exposed soil than in the rest of the field as a result of chronic plant water stress. Treatment of the clogged emitter problem had begun before the overflight, with sulfuric acid and chlorine flushes followed by a surfactant treatment to clear calcium deposits, algae, and sediment from the drip lines. The resulting water stress map (lower half of Fig. 4) using the VIT trapezoid showed no water stress in the smaller clogged area and some stress remaining in the larger area. This indicated that plants in the smaller area had recovered quickly while plants in the larger area were responding more slowly. Subsequent ground observations showed good recovery of plants in both areas.

Also of interest were the small orange patches in the upper right portion of the CWSI image in Fig. 4 (see the pointer <), which were postharvest remnants of a melon crop that had not been irrigated for 2 weeks. The gray area just left of center at the bottom of the field (see the pointer >) indicated a leak in the drip system in the vicinity of the flushout manifold. White areas on the image represented VIT points that fell outside the bounds of the trapezoid, generally below the bare soil line. These seemed to occur most often with artificial structures such as concrete irrigation canals or in uncultivated areas. It could not be determined if the yellow at some field edges actually indicated plant stress or was an artifact caused by camera distortion leading to misalignment of the images.

The top half of Fig. 5 is a thermal image of four melon field sections with equal water application rates, but a lower plant density in the middle caused by nematode damage. The CWSI image in the lower half of the figure shows that the increased water demand of the denser stand in the right section is not being entirely met, although plant water stress remains mild. A large wet area outside of the field is visible in gray at the bottom of the image (see the pointer <).

The major disadvantage to the remote sensing method of irrigation scheduling is that it only provides a snapshot of a crop's water status at the moment the image was taken. Monitoring crop stress from aircraft daily to time flood irrigations precisely or adjust the duration of drip irrigations would be prohibitively expensive. The processed imagery could, however, be used in conjunction with existing ET models. The model constantly monitors meteorological conditions to estimate water consumption and time of the next irrigation for an ideal crop, and periodic CWSI images could be used to check the model's accuracy and make adjustments based on actual crop water status. In the foreseeable future, ET-growth models and multispectral imagery will be combined in a digital map-based decision support system, so that each portion of a field can be irrigated with maximum efficiency.

Because the images were registered and processed manually, producing a finished CWSI map was very time consuming. Irrigators typically need information that is <24 h old, and the procedure must be automated to allow rapid delivery before the method can become commercially viable.

Conclusions

Combining a spectral vegetation index and surface temperature to form a two-dimensional stress index that obviates the need for complete vegetative cover appears feasible. The empirical method requires knowledge of surface conditions to the extent that trapezoid vertices can be determined, but more difficult inputs such as aerodynamic resistance and soil heat flux need not be known. Image processing must be automated to allow delivery of the information to the grower in a short enough time to be useful.

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